

Extreme isolation of WN3/O3 stars and implications for their evolutionary origin as the elusive stripped binaries

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ABSTRACT

Recent surveys of the Magellanic Clouds have revealed a new subtype of Wolf-Rayet (WR) star with peculiar properties. WN3/O3 spectra exhibit both WR-like emission and O3 V-like absorption — but at lower luminosity than O3 V or WN stars. We examine the projected spatial distribution of WN3/O3 stars in the LMC as compared to O-type stars. Surprisingly, WN3/O3 stars are the most isolated of all classes of massive stars; they are even farther away from O-type stars than red supergiants dominated by initial masses of 10–15 M_{\odot} , and far more dispersed than classical WR stars or luminous blue variables (LBVs). Their lack of association with O stars suggests strongly that WN3/O3 stars are not the descendants of single massive stars (30 M_{\odot} or above). Instead, they are likely products of interacting binaries at lower initial mass (10–15 M_{\odot}). Comparison with binary models suggests a probable origin with primaries in this mass range that were stripped of their H envelopes through non-conservative mass transfer by a low-mass secondary. Alternatively, their isolation could be partly due to kicks in rare cases where the secondary explodes first. We show that model spectra and positions on the Hertzsprung-Russell diagram for binary stripped stars are consistent with WN3/O3 stars. Monitoring radial velocities with high-resolution spectra can test for the presence of low-mass companions or runaway velocities. With lower initial mass and environments that avoid very massive stars, in contrast to classical WR stars, the WN3/O3 stars fit expectations for progenitors of Type Ib and possibly Type Ibn supernovae.

Key words: stars: evolution — stars: massive — stars: winds, outflows — stars: Wolf-Rayet

1 INTRODUCTION

Wolf-Rayet (WR) stars represent a late evolutionary phase when massive stars have been stripped of their H envelopes, exposing the He core (see [Crowther 2007](#) for a review). Most WR stars come in two main varieties, with spectra dominated by either nitrogen (WN stars) or carbon (WC stars). A third type, WO stars, are the most stripped but are extremely rare. (We exclude a fourth type, the WNH stars, which are H-rich and are likely to be very massive strong-winded stars near the end of the main-sequence; see [Smith & Conti 2008](#).) The two dominant mechanisms proposed for removing the H envelopes to make most of the H-poor WR stars are stellar winds or binary mass transfer. Both may be

at work, and their contributions to the population of WR stars may differ with initial mass and metallicity.

The standard single-star view, often referred to as the “Conti scenario” ([Conti 1975](#)), holds that WR stars are the descendants of the most massive O-type stars by virtue of their own mass loss. Their powerful radiation-driven winds act over the lifetime of the star to drive off its outer layers, so that all stars above some initial mass threshold (35 M_{\odot} , for example, but this depends on metallicity and details of mass-loss prescriptions; [Renzo et al. 2017](#)) will end their lives as WR stars. In this view, all stars above the threshold will yield WN stars first, but only stars with the highest luminosities (and the highest initial masses) can produce WC or WO stars ([Groh et al. 2013](#)). For lower initial mass where the winds are not strong enough, stars will die as H-rich red supergiants (RSGs) and Type II-P supernovae (SNe), with a narrow range in between where stars may

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explode in a brief transitional luminous blue variable (LBV) phase (Groh et al. 2013).

Over the years, the Conti scenario has found support in comparisons between model predictions and the observed number ratios of different types of stars in nearby galaxies (Meynet et al. 2011; Meynet & Maeder 2003; Massey 2003). However, some considerations have begun to unravel this paradigm as the dominant mechanism controlling the evolution of massive stars. Recent estimates of mass-loss rates have been revised downward, and are lower than mass-loss rates adopted in most models (see Smith 2014 for a recent review). These weaker winds would then require the assistance of eruptive mass loss from LBVs to completely shed the H envelopes and turn massive stars into WR stars (Smith & Owocki 2006). However, LBVs cannot participate in this evolutionary sequence of single massive stars as envisioned in the models, since their isolated environments require that they must be primarily the products of binary interaction (Smith & Tombleson 2015).

A different explanation for the origin of WR stars acknowledges that interacting binary systems exist in large numbers and have a profound influence on evolution (Paczynski 1971). Mass transfer in interacting binaries can operate over a wide range of initial mass, so it can lead to stripping of the H envelope in stars that are not luminous enough to do so with their own winds, and it can help strip the H envelope at low metallicity (Götzberg et al. 2017). The large binary fraction dictates that mass transfer and mergers will dominate the observed statistics of massive stars (Sana et al. 2012; Kobulnicky et al. 2014; Moe & Di Stefano 2016). Statistics of the observed fractions of SN subtypes (Smith et al. 2011) as well as the physical properties derived for individual stripped-envelope SNe (Drout et al. 2011; Dessart et al. 2011; Hachinger et al. 2012; Kim et al. 2015; Lyman et al. 2016; Yoon et al. 2017) strongly favor the interpretation that most stripped envelope SNe (Types Ic, Ib, Iib) arise from relatively low initial mass progenitors that were stripped of their H envelopes in binaries. Since very massive stars might in some cases collapse to a black hole without a bright SN display, it remains unclear what fraction of stripped-envelope SNe, if any, arise from classical single WR star progenitors. Moreover, the fraction of the observed population of WR stars that are produced primarily by interacting binaries, as opposed to arising from single-star mass loss, remains uncertain and debated.

In an effort to have a more complete census of WR stars and their subtypes in nearby environments, Massey and collaborators have been conducting a modern interference-filter imaging survey of the Magellanic Clouds, and they have reported results for the first three years of their ongoing study (Massey et al. 2014, 2015, 2017). Among the results is the discovery of a new and peculiar category of WR stars called WN3/O3 stars. These have spectra that show composite properties, with emission lines similar to early WN stars, but also absorption features of O3 V stars. However, Massey et al. point out that these are far too faint to be simple composite spectra of binary WN + O3 V systems. Such a pairing also seems unlikely, since the lifetimes of O3 V stars are too short to allow a companion to evolve to the WN phase (Massey et al. 2014). Massey et al. therefore conclude that this is a new type of WR star, not simply two stars contributing to the spectrum. Comparison of WN3/O3 spectra with

model atmosphere codes points to high photospheric temperatures (80,000-100,000 K), a factor of 10 enhancement in N abundance, H depletion, luminosities around $10^5 L_{\odot}$, and relatively low mass-loss rates of $\sim 10^{-6} M_{\odot} \text{ yr}^{-1}$ (Massey et al. 2014; Neugent et al. 2016, 2017). The absolute *V* magnitudes of WN3/O3 stars are roughly -2 to -3 mag, a few magnitudes fainter than classical WN stars, at -3 to -6 mag (Crowther 2007). Their evolutionary origin is uncertain, as such stars are not expected at these low luminosities in single-star evolution models at LMC metallicity. Massey et al. mention the possibility that they are the products of quasi-chemically homogeneous evolution, where extremely rapid rotation has mixed all the H into the burning core, rather than stripping of the H by winds.

The local environments of evolved massive stars and SNe can provide important clues about their lifetimes, and may provide insight to their previous evolutionary path. Typically, the WN3/O3 stars discovered so far do not appear in dense clustered environments where the most massive stars reside (Massey et al. 2014, 2015, 2017). Massey et al. (2015) suggest that at first glance, however, there is nothing special or unusual about the spatial distributions of WN3/O3 stars as compared to classical WR stars, since they are scattered across similar regions of the LMC (see their Figure 8). Massey et al. (2015) therefore conclude that their environments do not point to a different progenitor population as compared to normal WR stars.

In this paper we first take a closer look at the environments of WN3/O3 stars. In particular, we use the same analysis technique used previously by Smith & Tombleson (2015) to investigate the environments of LBVs, by measuring the projected separation on the sky to the nearest O-type stars. This provides a diagnostic of the relative age in the very nearby vicinity. The main result of this analysis is that the WN3/O3 stars are surprisingly dispersed on the sky, showing no correlation with O-type stars. This limits their initial masses to be well below $18 M_{\odot}$ (that of late O-type main sequence stars), and provides very strong implications for their previous evolution.

We therefore compare the WN3/O3 stars with model predictions including single and binary star evolution. In particular, we consider new atmosphere models for stars that have been stripped of their H envelope through binary evolution (Götzberg et al. 2017), showing that the characteristic mix of absorption and emission features in WN3/O3 stars is naturally reproduced by these models. Altogether, we find that the spectral features, the remote location, their low luminosities with respect to other WR stars and their rate can all be readily explained if WN3/O3 stars belong to the theoretically predicted class of elusive He stars that formed through Roche-lobe overflow in a binary system.

2 OBSERVED ENVIRONMENTS OF WN3/O3 STARS

So far, ten WN3/O3 stars have been discovered in the LMC, reported in three sequential papers (Massey et al. 2014, 2015, 2017). These ten objects with absolute magnitudes (M_V) and coordinates are listed in Table 1.

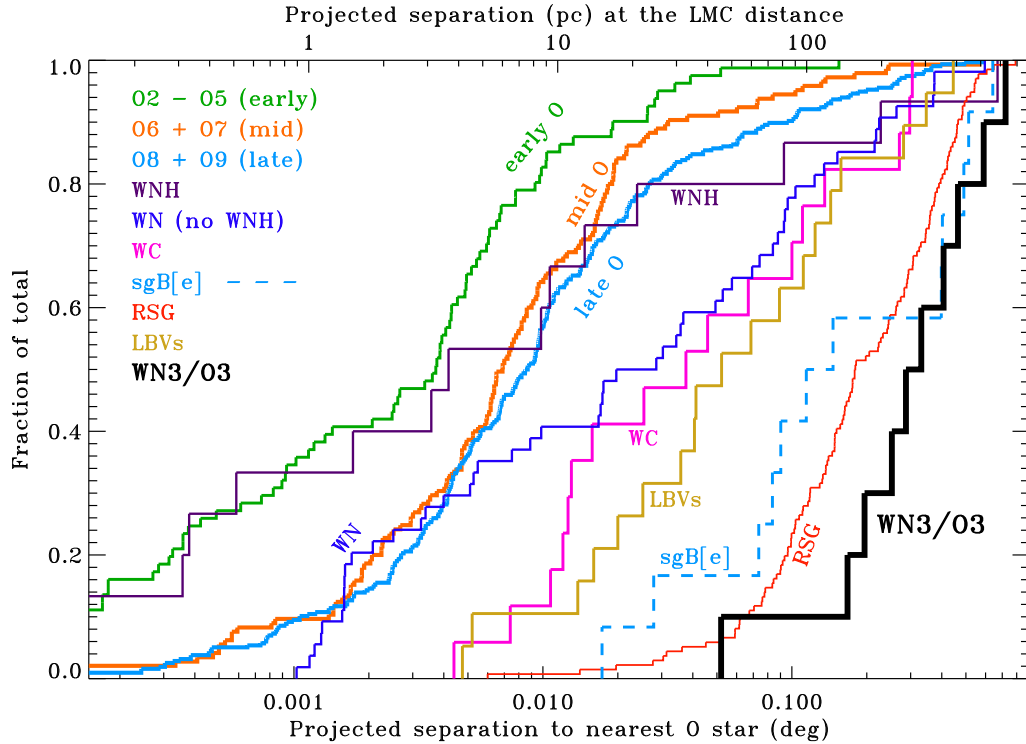


Figure 1. A cumulative distribution plot of the projected separation on the sky between various types of massive stars and their nearest O-type neighbor in the LMC. This is very similar to Figure 4 of [Smith & Tombleson \(2015\)](#), except that we now include the new class of WN3/O3 stars, and we also separate WNH and classical WN stars as noted previously by [Smith \(2016\)](#). See [Smith & Tombleson \(2015\)](#) for further details.

Table 1. LMC WN3/O3 stars and the projected separation (S) to the nearest O-type star

Name	Ref.	α_{2000}	δ_{2000}	M_V (mag)	S (deg)
LMC079-1	(1)	05 07 13.33	-70 33 33.9	-2.8	0.7218
LMC170-2	(1)	05 29 18.18	-69 19 43.2	-2.9	0.1959
LMC172-1	(1)	05 35 00.90	-69 21 20.2	-3.0	0.0520
LMC174-1	(1)	05 40 03.57	-69 37 53.1	-3.0	0.3310
LMC199-1	(1)	05 28 27.12	-69 06 36.2	-2.3	0.2522
LMC277-2	(1)	05 04 32.65	-68 00 59.7	-3.1	0.4068
LMCe159-1	(2)	05 24 56.89	-66 26 44.5	-2.6	0.2873
LMCe169-1	(2)	05 21 22.84	-65 52 49.0	-1.8	0.5897
LMCe078-3	(3)	05 41 17.50	-69 06 56.2	-2.2	0.1673
LMCe055-1	(3)	04 56 48.72	-69 36 40.3	-2.8	0.4646
LMC143-1	(1)	05 35 28.52	-69 40 08.9	-4.8	0.0167
LMC173-1	(1)	05 37 47.62	-69 21 13.6	-4.3	0.2191

S is the projected separation on the sky in degrees between an WN3/O3

star and its nearest O-type star neighbor of any subtype or luminosity class. References for discovery, M_V , and coordinates: (1) [Massey et al. \(2014\)](#); (2) [Massey et al. \(2015\)](#); (3) [Massey et al. \(2017\)](#). The last two entries, LMC143-1 and 173-1, have later O-type companions and have detected radial velocity variations consistent with being O+WN binaries. They are not true WN3/O3 stars, and we do not include these in our analysis, but we note their projected separations here.

To constrain the likely evolutionary history of the new class of WN3/O3 stars, we adopt the same analysis technique used previously by [Smith & Tombleson \(2015\)](#) to investigate the environments of LBVs. The analysis is to measure the projected separation on the sky (S in degrees) between individual stars of a certain class and their nearest O-type star neighbor, and to then compare the distribution

of these separations to those of other types of massive stars. We measure the distance to the nearest O star of any subtype, which is dominated by later-type O8-O9 stars; this provides the best comparison for all but the most massive stars, where a comparison restricted to only early O types would be appropriate ([Smith 2016](#)). [Smith & Tombleson \(2015\)](#) calculated values of S for LBVs in the LMC and SMC, and compared that distribution to the distributions of S for early, mid, and late O-type stars, WR stars and their subtypes, RSGs, and B[e] supergiants. By comparing the separations of LBVs, O-type stars, and WR stars, [Smith & Tombleson \(2015\)](#) demonstrated that LBVs cannot be a transitional stage between O stars and WR stars as envisioned in the single-star paradigm, and concluded that they must be the product of interacting binaries, either by rejuvenation through mass transfer or mergers, or by receiving a kick from a companion star's SN explosion.

We adopt the same technique and comparison data here, so we refer the reader to [Smith & Tombleson \(2015\)](#) for further details. The basic idea is that O-type stars are mostly born in clusters and associations, so that the average observed separation between O stars starts out small, but slowly grows with time as unbound clusters drift apart and as the most massive stars die off as SNe and remove themselves from the observed population. The most massive stars have short main-sequence lifetimes and small average separations, so their descendants must also have relatively small separations, only slightly larger than for early or mid O-type stars. Evolved stars that descend from lower initial masses (late O-type or early B-type stars, for example) are skewed

to larger separations. Different evolutionary stages that are sequential should move in-step from left to right on Figure 1. Adopting a simple model for the passive dissolution of star clusters, Aghakhanloo et al. (2017) demonstrated that the observed distributions of early, mid, and late-type O stars from Smith & Tombleson (2015) could be explained quantitatively with a secular drift velocity of $10\text{--}20\text{ km s}^{-1}$ and the expected ages of single O-type stars. They confirmed that the observed separations of LBVs, however, cannot be explained by the same model of drifting single stars, so that LBVs require longer lifetimes than allowed for single stars of their observed luminosity, or significant kicks.

We measured the projected separation on the sky to the nearest known O-type star (of any subtype) for the ten known WN3/O3 stars, and these values are listed in Table 1. Figure 1 shows the cumulative distribution of these S values in black, as compared to distributions for other types of massive stars including early, mid, and late O-type stars (green, orange, and light blue, respectively), WNH (purple), WN (blue), WC (magenta), LBVs (mustard), B[e] supergiants (light blue dashed), and RSGs (red). Figure 1 is essentially the same as in Smith & Tombleson (2015), except that we have added WN3/O3 stars of course, and we also divided the other WR subtypes slightly differently, as explained by Smith (2016).

The end result in Figure 1 is quite surprising — *the new class of WN3/O3 stars is the most dispersed population among known types of evolved massive stars*, and it is vastly more isolated than classical WR stars. Whereas WNH stars have a median separation of $\sim 4\text{ pc}$, and H-poor WN stars have a median separation of $\sim 20\text{ pc}$, the WN3/O3 stars have a median separation from O-type stars of $\sim 300\text{ pc}$. Such large separations are similar to the tail end of the maximum separations between late O-type stars, and as such, the projected separations between WN3/O3 stars and O stars may be consistent with a chance projection among the field of O stars. In other words, the nearest neighboring O-type stars seen in projection probably have nothing to do with the actual birth population of WN3/O3 stars; O star siblings of the WN3/O3 stars are probably long-since dead. This implies that the initial masses of WN3/O3 stars is less than that of the lowest-mass O-type stars (about $18 M_{\odot}$). WN3/O3 stars appear even more isolated from O-type stars than RSGs in the LMC, which, as noted by Smith & Tombleson (2015), are mostly stars with initial masses of around $10\text{--}15 M_{\odot}$. This gives a strong indication that the WN3/O3 stars have long lifetimes commensurate with H-burning main sequence lifetimes of relatively low initial masses of $10\text{--}15 M_{\odot}$.

Their progenitors are a vastly different population from those of the classical WN and WC stars, which arise from stars of $\sim 30 M_{\odot}$ or more. For example, a Kolmogorov-Smirnov (KS) test to quantify the significance of the difference in O-star separation distributions for normal WN stars and WN3/O3 stars yields a p -value of 4.9×10^{-5} ; i.e. there is basically no chance that normal WN stars and WN3/O3 stars are drawn from the same parent distribution. In contrast, a KS test comparing the WN3/O3 distribution to that of RSGs yields a p -value of 0.16, consistent with these two groups arising from the same parent distribution. In other words, if the WN3/O3 stars had been born as single stars, they would most likely be in the RSG population within the same range of initial masses and ages.

Single stars with initial masses around $10\text{--}15 M_{\odot}$ do not have strong enough mass loss to shed their H envelopes via winds. WN3/O3 stars are therefore not likely the product of mass stripping in binaries, and we discuss the evolutionary implications in Section 4.

3 POSSIBLE SELECTION EFFECTS

With any analysis of a cumulative distribution, one must consider selection effects and how completeness of the comparison samples may influence the results. The survey by Massey et al. that revealed the existence of the WN3/O3 stars is still underway, so additional WN3/O3 stars may yet be out there. This is immaterial, though, since our study investigates the local environment for each star by documenting the nearest O star; their overall distribution within the host galaxy is not considered.

Within the surveyed area, Massey et al. argue that their detection of WN3/O3 stars is complete, noting that their 5σ detection limit was at least a magnitude fainter than the observed WN3/O3 stars. Massey et al. (2015) took this as a strong indication that they are not missing a fainter population of WN3/O3 stars. If the WN3/O3 sample is complete in the surveyed area, what about the comparison O stars? Indeed, it is reasonable to wonder if the census of late O8-O9 dwarfs in the LMC, which dominate the field O stars, may be somewhat incomplete. As noted by Smith & Tombleson (2015), though, we can ask what effect it would have if we randomly peppered the LMC field with additional O-type stars. In that case, WN3/O3 stars might shift slightly to the left in Figure 1, but importantly, so would the RSGs, B[e] supergiants, LBVs and WR stars, because they would all be more likely to have a slightly nearer O-type neighbor as well. As such, WN3/O3 stars would remain the most isolated as compared to other types of evolved massive stars. In other words, correcting for randomly distributed but undetected field O stars isn't going to change the similarity between the distributions of WN3/O3 stars and RSGs, which are dominated by relatively low initial masses.

What would be needed to make WN3/O3 stars agree with other WR stars is to have so-far unrecognized O star associations located preferentially around the WN3/O3 sample of objects. Since even a typical O9 main sequence star in the LMC is about a magnitude brighter at visible wavelengths than any of the WN3/O3 stars, it seems unlikely that most of the WN3/O3 stars reside amid clusters or associations of O stars that have escaped detection.

A more plausible scenario may be that selection effects make it difficult to detect relatively faint WN3/O3 stars that reside in crowded regions next to much brighter O-type stars. However, one would only expect the glare of brighter stars to hinder the detection of fainter WN3/O3 stars if they are at small separations (closer than $\sim 5''$, for example, or $1\text{--}2\text{ pc}$ projected separation). In that case, though, the population of WN3/O3 stars would be highly bimodal, with some far on the left of Figure 1, and the rest far on the right, so we would need to invoke two populations of WN3/O3 stars. Barring this, it seems that the observed isolation of WN3/O3 stars is robust.

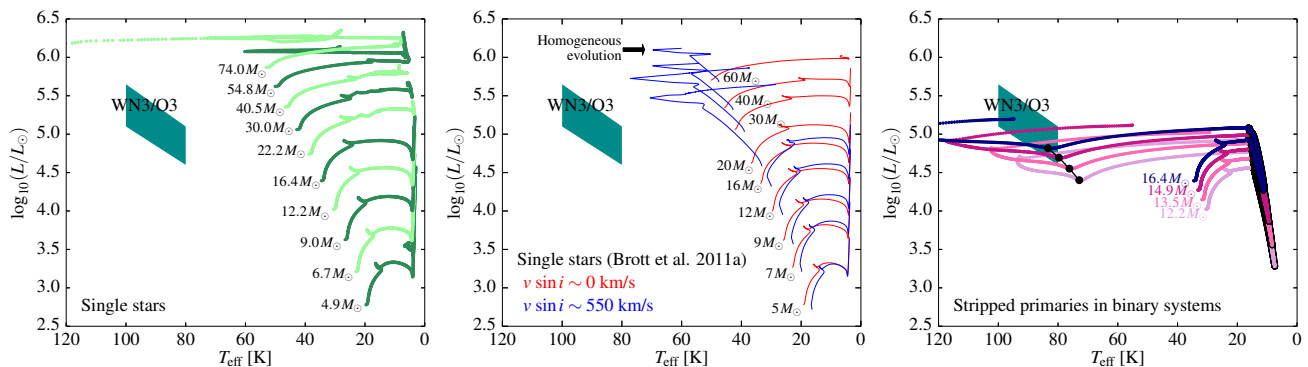


Figure 2. Hertzsprung-Russell diagrams showing the approximate location of the observed WN3/O3 stars in shaded green. Left panel shows MESA evolutionary tracks for single stars (see text Section 4.1.1). Middle panel shows models of extremely rapidly rotating stars by [Brott et al. \(2011a\)](#) in blue with the corresponding non-rotating tracks for comparison in red. (Note that the He burning phase of the homogeneous evolutionary tracks are not available.) Right panel shows tracks for the primary stars in binary systems ([Gotberg et al. 2017](#)). Black points show the location of stripped stars halfway through their He burning sequence. Labels indicate the initial masses at the onset of H burning.

4 EVOLUTIONARY ORIGIN

The observed properties of WN3/O3 stars pose an intriguing puzzle for evolutionary models. Here we consider and compare various evolutionary scenarios.

4.1 Comparison with Evolutionary Tracks

Figure 2 shows Hertzsprung-Russell (HR) diagrams, where we have marked the location of the observed WN3/O3 stars with a green diagonal box. This locus for the WN3/O3 stars is based on the values of $T_{\text{eff}} = 80,000$ to $100,000$ K and $\log(L/L_{\odot}) = 5.6$ derived for the WN3/O3 star LMC170-2 by [Massey et al. \(2014\)](#). The range in L shown here is determined by the range of different observed values of M_V in the full sample scaled with the same bolometric correction as LMC170-2. This location in the HR diagram is quite approximate, and further data and analysis will be needed to determine the physical parameters of the WN3/O3 stars more accurately. The implied bolometric luminosities will also be lower than shown here if it is determined that faint companions make a contribution to the V -band flux. Here, we provide a preliminary comparison with evolutionary tracks.

4.1.1 Single stars with wind mass loss

In the left panel of Figure 2, we show a sequence of evolutionary tracks for non-rotating single stars computed with the MESA evolutionary code ([Paxton et al. 2011, 2013, 2015](#)), using the same assumptions as listed in [Gotberg et al. \(2017\)](#). The tracks show the evolution from the onset of hydrogen burning until the completion of central carbon burning for a metallicity of $Z = 0.004$ using standard wind mass-loss rate recipes ([de Jager et al. 1988](#); [Nieuwenhuijzen & de Jager 1990](#); [Vink et al. 2000, 2001](#)).

Only the most massive models shown here reach into the regime of classical WR stars, and they are too luminous for most WN3/O3 stars. Allowing single star models to reach the location of the WN3/O3 stars would require significantly higher mass-loss rates. This may be a reasonable option to

consider, given the large uncertainties in our understanding of mass loss (for a review see [Smith 2014](#)). Stars with masses between about 40 and $60 M_{\odot}$ may have significantly higher mass loss rates than adopted in these models if they experience LBV-like instability, which may be insensitive to metallicity ([Smith & Owocki 2006](#)). However, these high-mass stars are expected to have much higher wind mass-loss rates when they reach the WR phase, as compared to the WN3/O3 stars, and LBVs are now thought to be mostly a product of binary evolution anyway ([Smith & Tombleson 2015](#)). Moreover, such high-mass stars have lifetimes that are far too short to be consistent with the spatial distribution of WN3/O3 stars (Figure 1); single stars with longer lifetimes at lower masses (10 – $20 M_{\odot}$) never evolve so far to the blue. This makes it very unlikely that the WN3/O3 stars arise from traditional high-mass single stars that shed their H envelope through winds.

4.1.2 Rotating stars evolving chemically homogeneously

In the middle panel of Figure 2 we show evolutionary tracks of single stars with extremely high initial rotation rates (blue) published by [Brott et al. \(2011a\)](#). These have equatorial velocities over 500 km s^{-1} initially, which is near their critical rotation rate. Tracks for non-rotating single stars computed with the same physical assumptions are shown for reference in red. These models adopt a metallicity $Z = 0.0047$. At the higher initial mass range, the very rapidly rotating stars experience internal mixing processes that cause them to evolve chemically homogeneously ([Maeder 1987](#); [Yoon & Langer 2005](#)). They become brighter and bluer during their main sequence evolution. After completing central He burning they are expected to contract ([Yoon et al. 2006](#)). This is not shown in the diagram, since [Brott et al. \(2011a\)](#) do not provide the complete post main sequence evolution. They will move blue-ward at nearly constant bolometric luminosity to form bright massive He stars. As above, such extremely rapidly rotating models could approach the upper bound of the area in the diagram where the brightest WN3/O3 stars reside, but it could not explain the lower end of the range of luminosity observed for WN3/O3 stars. This

scenario would, however, require very extreme rotation rates and would still imply masses that are higher than we infer from their location (Section 2). This, again, makes rapidly rotating single stars a very unlikely explanation.

Instead of rapidly rotating single stars, it is worth considering whether WN3/O3 stars could be the product of rapidly rotating stars that are produced by spin-up during mass transfer in a binary system (Packet 1981; Cantiello et al. 2007; de Mink et al. 2013). An attractive feature of this explanation is that the rapidly rotating star can become a runaway star when its companion star explodes (Hoogerwerf et al. 2001; Blaauw 1961). This may provide a possible explanation for the extreme isolation of the brightest WN3/O3 stars, which can be tested by investigating the kinematics of these stars. If they do not have relatively large radial velocities or proper motion, then this scenario is not valid (see Aghakhanloo et al. 2017, for a similar issue regarding LBVs). The dimmer WN3/O3 stars seem hard to reconcile with this scenario. It is also unsatisfactory that the WN3/O3 stars do not appear to show signs of rapid rotation.

It should be noted that the theoretical concept of chemically homogeneous evolution is not without controversy. It recently gained renewed popularity in the context of gravitational wave progenitors (Marchant et al. 2016; Mandel & de Mink 2016). However, the validity of the treatment of mixing processes in these 1D models at such high rotation rates is debated and appears to be at tension with surface abundance measurements (Hunter et al. 2009; Brott et al. 2011b). Although we do not have data at present to rule out this evolutionary path, the requirement of extreme rotation rates combined with other challenges makes it seem like a rather exotic explanation in comparison to the more natural and expected scenario that we present next.

4.1.3 Stars stripped by a binary companion

The right panel of Figure 2 shows the evolution of the primary stars in binary systems that are stripped of their H envelope through Roche-lobe overflow. These models are computed with the same assumptions as detailed in Götzberg et al. (2017) for a metallicity $Z = 0.004$. They are part of a larger grid that will be presented in Götzberg et al. (in prep.).

For several of the evolutionary tracks for stripped star models, we find that they spend their long-lasting core-He burning phase in the lower-luminosity end of the region of the WN3/O3 stars. These stripped stars come from stars with initial masses between $12\text{--}16 M_{\odot}$, which is in very good agreement with the range of initial masses that we infer from their spatial distribution. This agreement makes such a scenario seem promising.

The tracks shown here only show the mass losing primary star. The companion is not shown. The observed WN3/O3 stars have their optical spectrum dominated by the He star, and do not show obvious signs of a luminous mass-gainer companion like a Be star. Below we consider two possibilities. Either the companion is a low-mass star that does not significantly contribute to the observed spectrum, or instead, the companion has already exploded. The latter requires reversal of the SN order. This has been seen in theoretical models by Pols (1994), but only for a very limited range of parameter space. Thus, this channel is difficult to rule out, but should be very rare. We consider the

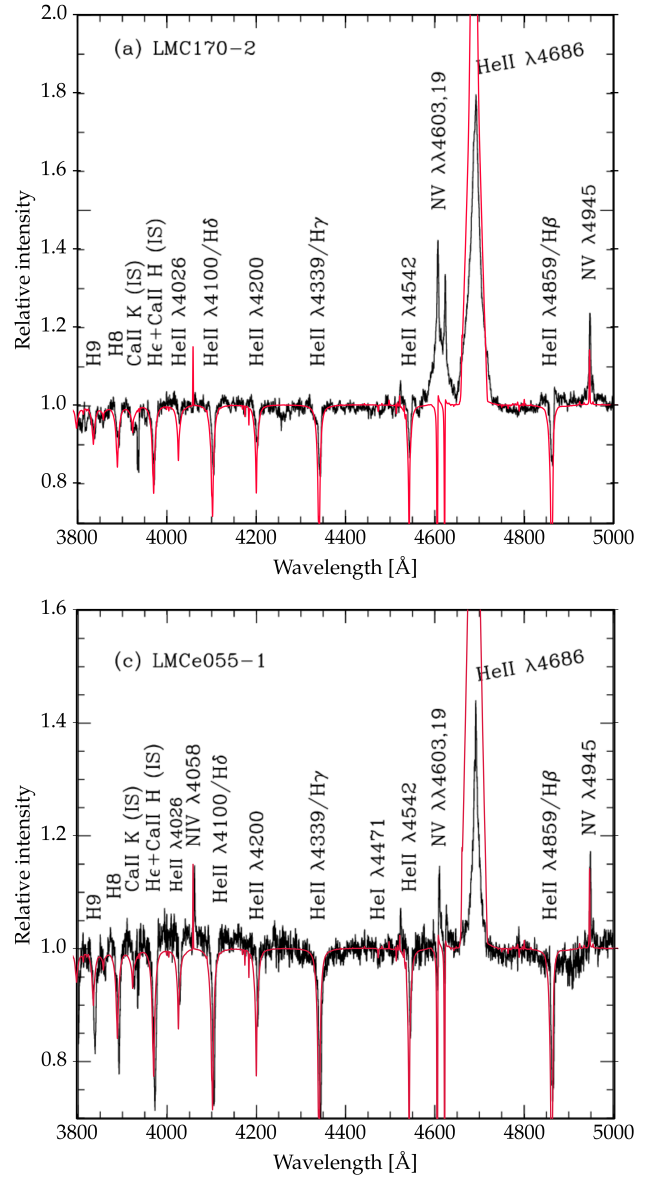


Figure 3. Top: The observed WN3/O3 star LMC170-2 from Massey et al. (2014) plotted together with a stripped star model of mass $4 M_{\odot}$, originating from an initially $12 M_{\odot}$ star. The metallicity of the model is $Z = 0.004$. Bottom: The same model now plotted over the observed spectrum of the star LMCe055-1, from Massey et al. (2017).

first possibility to be more likely, where the WN3/O3 is the remnant of a star stripped by a low-mass companion. This case implies that the companion was low mass initially and evolved through non-conservative mass transfer, preventing it from accreting a substantial fraction of the mass of the donor. This will be discussed in more detail below when we estimate rates.

4.2 Spectral models of WN3/O3 stars

WN3/O3 stars show peculiar spectra with signatures of high T_{eff} and a mix of emission and absorption lines. This imme-

diately caught our attention as very similar to theoretical models recently presented by [Gotberg et al. \(2017\)](#). Spectral models of stripped stars have also been computed by [Kim et al. \(2015\)](#), but these are for much cooler pre-SN phases, where the spectra show very different characteristics. In Figure 3 we show the observed normalized spectra of two example stars (black) from [Massey et al. \(2014\)](#). The top panel shows the WN3/O3 star LMC170-2 for which [Massey et al. \(2014\)](#) presented CMFGEN spectral modeling. The lower panel shows the somewhat cooler WN4/O4 star LMCe055-1, which is observed to be member of an eclipsing binary with a 2 day orbital period ([Graczyk et al. 2011](#)). In red, we overplot theoretical spectra from one of the atmosphere models that we made for stars that are stripped by a binary companion. These models were computed using the CMFGEN atmosphere code ([Hillier & Miller 1998](#)) for stripped stars produced with the stellar evolutionary code MESA, as detailed in [Gotberg et al. \(2017\)](#), with the exception that here we use a terminal wind velocity $v_\infty = 1.9 \times 10^3 \text{ km s}^{-1}$. The model shown here is for a $4 M_\odot$ stripped star (i.e. He star) originating from star with an initial mass of $12 M_\odot$.

No attempt has been made to obtain a good fit to the spectrum. The model was calculated previously as part of a grid of evolutionary models, and is shown here for comparison only. Interestingly, the peculiar combination of absorption and emission features that characterize the observed WN3/O3 spectra are generally reproduced very well for LMC170-2, and the correspondence is even better for LMCe055-1. The He II $\lambda 4686$ flux is overestimated in the model, but the strength of the He emission features is very sensitive to the wind mass-loss rate and the terminal wind velocity, which are both uncertain quantities. In our models we use the wind mass-loss recipe by ([Nugis & Lamers 2000](#)) that has been extrapolated to lower L . For the terminal wind velocity, we use the value corresponding to 1.5 times the surface escape speed. So far, the wind mass-loss rate and terminal velocity have not been constrained by observations in this regime. It is therefore not surprising if these parameters may need some adjustment, which could be done without changing the overall properties. The atmosphere model underestimates the N V $\lambda\lambda 4604, 20$ flux, especially in the case of LMC170-2, but it matches much better for LMCe055-1. This spectral feature is very sensitive to the wind density and ionization stage. Tuning these parameters is also possible without losing the general characteristics and should lead to refined measurements of the mass-loss rate and temperature.

The atmosphere model shows emission for N IV $\lambda 4058$, which is observed to be in emission for LMCe055-1, but not for LMC170-2. This line is sensitive to the temperature. LMCe055-1 appears to be somewhat cooler than LMC170-2. Note that we adopted the same 80,000 - 100,000 K temperature for all WN3/O3 stars to derive their range of luminosities in Figure 2. Using lower temperatures would translate to lower luminosities for some stars (since we scaled from their M_V), thus widening the disagreement with single-star models and rapidly rotating models even more. We expect that LMC170-2, which is on the brighter end of the distribution of visual magnitudes for WN3/O3 stars, may be better reproduced by a model of a somewhat more massive stripped star than the $12 M_\odot$ example shown here.

In Table 2 we compare the parameters for our atmo-

Table 2. Comparison of the parameters of the spectral fit to the observed WN3/O3 star LMC170-2 as presented by [Massey et al. \(2014\)](#) with our atmosphere model for a $4 M_\odot$ stripped star originating from an originally $12 M_\odot$ primary star in a binary system ([Gotberg et al. 2017](#)).

Parameter	Fit to LMC170-2	Our $4 M_\odot$ Model
T_{eff} [kK]	80-100	73
He/H	~ 1	0.57
$X_{\text{N,s}}[X_{\text{N,s}}, \odot]$	10	2.3
$\dot{M}_{\text{wind}} [M_\odot \text{ yr}^{-1}]$	$0.8 - 1.2 \times 10^{-6}$	1.6×10^{-7}
f_{vol}	0.1	0.5
$\log_{10}(L/L_\odot)$	5.3-5.6	4.4
$\log_{10}(g/\text{cm s}^{-2})$...	5.1
$v_\infty [\text{km s}^{-1}]$...	1.9×10^3
$R_{\text{eff}} [R_\odot]$...	1.0
$M_V [\text{mag}]$	-2.9	-0.53

We use the following notation for the stellar properties: T_{eff} for

effective temperature, He/H for relative number fraction, $X_{\text{N,s}}$ for surface nitrogen mass fraction displayed in comparison to the solar value, \dot{M}_{wind} for wind mass-loss rate, f_{vol} for volume filling factor in wind clumping, L for luminosity, $\log_{10} g$ for surface gravity, v_∞ for terminal wind velocity, R_{eff} for effective radius.

sphere model to those presented by [Massey et al. \(2014\)](#), derived from their CMFGEN fit to LMC170-2. The mass-loss rate, T_{eff} , and luminosity are lower in our model. Our model also underestimates the brightness of LMC170-2 in the V-band. This may indicate that this star is somewhat more massive than our fiducial model, as noted above. It might also signify a contribution of visual-wavelength flux by a low-mass main-sequence companion star. In binary models, the secondary star is likely to be a rapid rotator as a result of mass accretion. Such a faint companion with broad spectral features may be difficult to recognize in the optical spectrum.

In summary, we conclude that our models reproduce the key spectral features (combination of absorption and emission lines) remarkably well, considering that none of the uncertain parameters have been adjusted to fit the observed characteristics.

4.3 Rate estimates

To explain WN3/O3 stars as stripped He stars we need them to either have a faint companion, or to be the former member of a disrupted binary system, as discussed above. The second possibility requires the secondary to explode before the primary, which should be very rare according to current standard simulations ([Pols 1994](#); [Claeys et al. 2011](#)), although this does depend on the treatment of convection and rejuvenation processes (e.g. [Braun & Langer 1995](#); [Dray & Tout 2007](#)). The case of a faint low-mass companion on non-conservative mass transfer may also be somewhat rare, but more likely than a reversal of the SN order.

A lower mass companion should be a less evolved star that still resides on the main sequence. Comparing the brightness of low-mass main-sequence star models ([Kurucz 1992](#)) to the model of stripped stars at optical wavelengths, we find that the spectral model of a stripped star presented above is brighter at optical wavelengths than main-sequence

stars with a late B spectral type (or fainter), suggesting the companion stars to have initial masses $M_2 \lesssim 4 M_\odot$. Systems with such extreme mass ratios and relatively long periods (more than about 300 days, [Schneider et al. 2015](#)), are thought to evolve through highly non-conservative mass transfer. This means that the companion will not gain a significant amount of mass, so that it remains faint even after mass transfer. It may, however, gain significant angular momentum to become a rapid rotator, as noted above.

Below, we estimate the relative number of stars that are stripped by a low-mass companion, based on the rough constraints on the initial period and mass ratio stated above. This allows us to provide a very rough estimate for the relative fraction of stars with initial mass of $\sim 12 M_\odot$ that become a stripped He star, with respect to $12 M_\odot$ stars that spend their He burning lifetime as RSGs.

(i) Massive stars are typically found with close companions. We assume that half of all $12 M_\odot$ stars are the primary of a binary system, $f_{\text{bin}} \approx 0.5$ ([Duchêne & Kraus 2013](#); [Moe & Di Stefano 2016](#)).

(ii) For an initially $12 M_\odot$ primary star, we estimate that the faint companion probably is less massive than about $4 M_\odot$. We assume a uniform distribution of mass ratios, which is consistent with observations ([Kobulnicky et al. 2014](#)). The fraction of systems with mass ratios in the appropriate range is thus $f_q \approx 0.25$.

(iii) We require initially wide binary systems, larger than about 300 days, to ensure non-conservative mass transfer and avoid a merger between the two stars ([Schneider et al. 2015](#)). (Note that 300 days is not necessarily the final period.) We assume the initial orbital periods to be distributed according to Öpik's law, which is a uniform distribution in the log of the period ([Öpik 1924](#)), between about 3 and 3000 days ([Kobulnicky et al. 2014](#); [Dunstall et al. 2015](#)). The fraction of systems wider than 300 days is thus $f_P \approx 0.33$.

(iv) Stripped stars spend approximately 10% of their lifetime in the stripped star phase. This time is set by the duration of the He burning phase. For stars that are not stripped, we assume they spend their lifetime as RSGs, with a similar duration. Since the lifetimes for each are comparable we do not need to explicitly account for this in our rate estimate.

The above considerations imply the ratio of observable stripped stars to RSGs resulting from stars with the same initial mass of approximately $12 M_\odot$, $f_{\text{strip}} = N_{\text{strip}}/N_{\text{RSG}}$, is a few percent,

$$f_{\text{strip}} \sim 0.04 \times \left(\frac{f_{\text{bin}}}{0.5} \right) \left(\frac{f_q}{0.25} \right) \left(\frac{f_P}{0.33} \right).$$

Comparing this directly to the currently observed number of WN3/O3 stars, $N_{\text{strip,obs}} = 10$, is tricky given the large uncertainties, biases that are not yet well understood, and incompleteness. [Neugent et al. \(2012\)](#) find of order 500 RSGs in the LMC, although these RSGs may span a wider mass range than the stripped binaries that we consider. Also the completeness fraction, f_{comp} of the survey of [Massey et al. \(2014\)](#) is uncertain for our purposes. In terms of finding stripped stars, [Massey et al.](#)'s search is probably not limited so much by the V magnitude of the stars, because they noted that the detection limit was significantly fainter than the WN3/O3 stars. Fainter stripped stars should exist, but

they will also have weaker winds, and hence, weaker emission lines. The weak emission lines rather than the fainter continuum may cause them to be missed in a narrow-band imaging survey. Of course, [Massey et al.](#)'s survey is not yet finished; significant portions of the LMC have yet to be surveyed, so it is possible that several more WN3/O3 stars will be discovered in the LMC.

Nevertheless, adopting very rough but plausible fiducial number estimates for the comparison RSGs, the fraction of stars in this mass range that are stripped primaries, and some completeness factor can yield a number of stripped stars that matches the sample of WN3/O3:

$$N_{\text{strip,obs}} \sim 10 \times \left(\frac{N_{\text{RSG}}}{500} \right) \left(\frac{f_{\text{strip}}}{0.04} \right) \left(\frac{f_{\text{comp}}}{0.5} \right)$$

We emphasize that is an extremely crude estimate, which should only be considered as an order of magnitude assessment. We conclude from this that the number of WN3/O3 stars found so far agrees reasonably well with the number of stripped primaries with low-mass companions that one expects from a population.

Interestingly, we expect a large majority of stripped stars to be difficult to see because they have a more massive mass-gainer companion that is too bright. The detection of these stripped stars will be discussed in a future paper, but in some of these cases we predict FUV-excess detection to be a promising technique.

4.4 Detection of companions

A strong clue that binarity may play a role in the formation of WN3/O3 stars comes from the system LMCe055-1, which is an observed eclipsing binary ([Graczyk et al. 2011](#); [Massey et al. 2017](#)), with a period of only ~ 2.2 days. Such a short orbital period is expected in the case of common envelope ejection. Obtaining the detailed system parameters for this system will be of great value to constrain models of mass transfer.

In general, a low-mass companion may be easily overlooked. It would not dominate the total flux at near-UV or visual wavelengths (by design). Given that its mass is low, its gravitational pull on the WN3/O3 star is also small. For wider orbits, radial velocities would have a low amplitude and would only be detectable with multi-epoch, high-resolution spectroscopy. Even then, the system requires a favorable inclination. Finally, there is still the option that these stripped He stars come from disrupted systems with no remaining companion. Such systems may stand out by a peculiar radial velocity, but for systems that are wide at the moment of disruption of the supernova, the radial velocity may be much less than the canonical threshold of 30 km s^{-1} for runaway stars.

[Massey et al. \(2014\)](#) note that LMC143-1 and LMC173-1 are classified as binaries containing WN3 + late O-type binaries (they are also brighter, and we do not consider them among the ten WN3/O3 stars discussed here; see Table 1). They mention an absence of evidence for binarity for the other stars, although this is discussed mostly in the context of binarity as an inadequate explanation for the composite emission/absorption nature of the observed spectra. Low-mass companions are much harder to rule out. For most of the objects in the sample, [Massey et al. \(2014\)](#) present only a

single epoch, which makes it difficult to detect radial velocity variations. Moreover, the spectra have only low/moderate resolution, with a resolving power $R \sim 4100$ (Massey et al. 2014, 2015, 2017). With these parameters, only large variations would be detectable for the short-period systems that have multiple epochs, even with an optimal cadence. One should be able to detect radial velocity variations greater than roughly $\Delta v \gtrsim \langle \sin i \rangle c/R \approx 60 \text{ km s}^{-1}$, where i is the inclination. (This rough estimate assumes a sufficient number of epochs, and does not account for the possibility to cross correlate multiple lines.) For a $4 M_{\odot}$ stripped star and $2 M_{\odot}$ companion, this implies an orbit shorter than 10 days. This may apply to systems that have evolved through common envelope ejection, but systems that formed through stable non-conservative mass transfer may well have orbits that are substantially larger than this.

We conclude that observational constraints so far do not preclude a binary origin for WN3/O3 stars. Dedicated multi-epoch spectroscopy at high resolution will be required to further investigate the binary nature of these objects.

4.5 Summary and testable predictions

We considered the hypotheses that WN3/O3 stars result from single stars, rapidly rotating stars that evolve homogeneously, or stripped stars in binary systems. We find that the latter possibility most naturally explains (1) the remote location of the WN3/O3 stars and the implication of this for the progenitor masses, (2) the peculiar spectra showing a mix of emission and absorption lines, and (3) the fact that they are under luminous compared to normal WR stars. We further find that this scenario (4) predicts rates that are roughly the right order of magnitude, and (5) is consistent with the current constraints on detections of companions for WN3/O3 stars presented by Massey et al. (2017). A critical next step is to test our hypothesis and verify whether WN3/O3 stars are indeed binary systems containing a stripped star together with a faint companion, or whether they exhibit any peculiar spatial velocities indicating that they come from disrupted binary system. If the stripped stars still have faint companions, the majority of the sample should have detectable radial velocity variations. This will require high-resolution spectra, since the variations may be small in many cases, as noted above.

For those systems that may have formed from binary systems where the secondary exploded first, their isolated environments require that they are slow runaways, and so they should exhibit peculiar space velocities. However, a complication is that reversal of the SN order requires conservative mass transfer and implies substantial widening of the system before explosion. The spatial velocities of such systems may not necessarily be high enough to be classified as runaway stars ($> 30 \text{ km s}^{-1}$) and may be difficult to distinguish as peculiar from the surrounding stellar population. Future proper motions with high precision may be a crucial test in this regard.

Detection of eclipses or ellipsoidal variations will be especially useful as they will provide tight constraints on the system parameters. LMCe055-1 is therefore an extremely interesting system for further study. However, eclipses are only expected for the closest systems or those whose orbits are favorably aligned.

5 SUPERNOVA PROGENITORS

The new WN3/O3 stars found by Massey et al. are less luminous and have lower mass-loss rates than classical WN stars. In this paper, we have shown that they also have much more isolated environments relative to O-type stars in the LMC; in fact, they are the most dispersed class of evolved massive stars we considered in the above comparison. This isolation requires that they have longer lifetimes and substantially lower initial masses than classical WN stars, comparable to normal RSGs with initial masses of $10\text{--}15 M_{\odot}$. This immediately points to binary evolution as a way to produce these H-poor stars in this mass range. In considering a wide range of binary scenarios, we find that a plausible evolutionary channel to explain WN3/O3 stars is that stripping of the primary star's H envelope occurs in a system where the secondary star is a relatively low-mass main sequence star ($< 4 M_{\odot}$), and where the separation is wide, such that mass transfer is non-conservative. In this case, the companion is substantially fainter than the WN3/O3 star primary and could be hidden in the spectrum. This is expected to be a minority of all cases of binary-stripped stars, but it is a majority of cases without a bright companion. We argued that the expected number of such stars in the LMC, while uncertain, is at least plausibly in agreement with the observed WN3/O3 stars.

In addition to matching the properties of WN3/O3 stars, the lower-mass stripped progenitors in binaries that we describe also do a good job of fitting expectations for the progenitors of many stripped-envelope SNe, especially those of Type Ib. Our example cases had initial masses of roughly $12\text{--}16 M_{\odot}$ and final masses as stripped He stars of only $4\text{--}5 M_{\odot}$. If these stars were to explode, and if $\sim 1.5 M_{\odot}$ goes into the neutron star, then they would have He-rich ejecta masses of roughly $2\text{--}2.5 M_{\odot}$. This agrees well with the average value of derived ejecta mass for SNe Ib, which is $\sim 2 M_{\odot}$ (Drout et al. 2011; Lyman et al. 2016). All the WN3/O3 stars in the LMC have absolute magnitudes that are fainter (roughly -2 to -3 mag) than published upper limits (-5 mag) for non-detections of Type Ib progenitors in pre-SN imaging (Smartt 2009), so they would be consistent with available constraints from direct imaging.

As noted in the Introduction, many lines of evidence now suggest that a large fraction of stripped-envelope SNe arise from relatively low-mass progenitors (initially $10\text{--}20 M_{\odot}$) in binary systems rather than from more massive progenitors ($> 35 M_{\odot}$) that have lost their H in winds to become classical WR stars before exploding. The lack of any direct detection (thus far) of a massive WR star as a stripped-envelope SN progenitor is consistent with a dominant binary scenario, although this is not necessarily conclusive since hot progenitors may be hard to detect in available progenitor imaging. The only reported detection of a progenitor to a stripped-envelope Type Ib explosion is the case of iPTF13bvn, where its progenitor is thought to have been a lower-mass helium giant (Eldridge & Maund 2016; Folatelli et al. 2016).

SNe I Ib are also stripped-envelope SNe, but in these cases a small mass of residual H (about $0.1 M_{\odot}$ or less) remains in the star's envelope at death. Direct detections of SNe I Ib progenitors and some of their potential surviving companions point to modest initial masses of $10\text{--}20 M_{\odot}$ and

binary origins for this sub-class of stripped stars as well (Aldering et al. 1994; Maund et al. 2004, 2011; Van Dyk et al. 2011, 2014; Fox et al. 2014).

Interestingly, two recent studies have searched for surviving companions of nearby SNe Ic (SN 1994I and SN 2002ap) and both find that any companion is less massive than $\sim 10 M_{\odot}$ (Van Dyk et al. 2016; Zapartas & et al. 2017). These systems require stripping in a binary with a low-mass companion that does not gain much mass, similar to the WN3/O3 star scenario that we discuss above.

The fact that WN3/O3 stars have a statistical separation from O-type stars resembling that of relatively low-mass RSGs is also interesting in comparison to the observed statistics of SN environments. While the locations of SNe Ic and SNe Ic-BL within their host galaxies tend to favor relatively young ages and high initial masses, the environments of SNe Ib are distinct and appear to be more like those of SNe II-P that arise mostly from older stars (Anderson & James 2008; Anderson et al. 2012).

Another SN type for which the WN3/O3 stars are potential progenitors is the class of Type Ibn explosions. These are stripped-envelope SNe that lack H, but have strong and narrow He lines (Pastorello et al. 2008; Hosseinzadeh et al. 2017). The narrow He lines are thought to be indicative of shock interaction with circumstellar material (CSM), requiring pre-SN eruptive mass loss akin to Type IIn supernovae (Smith 2014), but occurring in systems with a stripped-envelope progenitor.¹ Information about the environments of SNe Ibn is still admittedly somewhat anecdotal, since these are relatively rare and not many are known yet. However, it does appear that a subset prefers relatively faint, blue hosts and relatively remote locations within host galaxies. In particular, the two best-studied SNe Ibn so far, SN 2006jc (Pastorello et al. 2007; Foley et al. 2007) and SN 2015G (Hosseinzadeh et al. 2017; Shivvers et al. 2017) occurred in very sparse outer regions of their hosts. This is reminiscent of some extremely isolated SNe IIn, such as SN 2009ip (Smith et al. 2016). One SN Ibn was even seen to occur in an early-type galaxy (Sanders et al. 2013). Thus, it is not clear that SN Ibn environments necessarily point to massive WR-like progenitors. A quantitative analysis of SN Ibn host environments has not yet been conducted, however, so this link is tentative.

Thus, it is intriguing that the very isolated environments of WN3/O3 stars (at least compared to fairly massive O-type stars) implies that they fit the bill for binary-stripped progenitors from initially lower-mass stars than classical WR stars. They could be good examples of stripped-envelope SN progenitors where the companion star is too faint to be detected after a SN fades. We argue that this is most commonly because the companion is a faint, low-mass star where the system has experienced non-conservative mass transfer.

There will be more common cases where the secondary gains a significant amount of mass or had a relatively high

initial mass, in which case the companion may be so bright at optical wavelengths that it may be difficult to see the stripped star. Searches for nearby counterparts of these hot stripped stars hidden by bright companions are ongoing. So far, only a handful (5) candidates are known: ϕ Per, FY CMa, 59 Cyg, HD 45166, and HR 2142 (Peters et al. 2013, 2016; Groh et al. 2008; Steiner & Oliveira 2005). In all these systems, the candidate hot He star is extremely difficult to study because it orbits a cooler and brighter B or Be star. Thus, the fact that WN3/O3 stars seem to outshine their faint, low-mass companion provides an extremely valuable opportunity for detailed investigations of the physical properties of likely SN Ib progenitor stars.

Since they are relatively faint and hot, perhaps we are still missing many of the WN3/O3 stars in nearby environments. It would be interesting to try and detect more examples in the Milky Way and SMC. If they do not exist in the Milky Way (or if they are pushed to even lower initial masses), it may be because stronger winds at higher metallicity lead to emission line spectra that hide the O3 V-type absorption signatures, or alternatively, because of different physics of mass transfer due to more effective cooling at higher metallicity. Similarly, in the SMC, a strong metallicity dependence (Hainich et al. 2017) might lead to even weaker winds than in the LMC, causing the stars to lack emission altogether and to appear as anomalously faint O3 stars. In any case, it will be interesting to increase the sample size in order to explore their statistical properties further, and to identify them in other host galaxies to explore their metallicity dependence.

6 SUMMARY

We investigate the nature of the new class of WN3/O3 stars in the LMC reported by Massey et al. in three recent papers (Massey et al. 2014, 2015, 2017). Using an analysis of their environments similar to the study of LBVs by Smith & Tombleson (2015), we find that their observed distribution of separations from O-type stars on the sky shows that they are much more isolated than other types of WR stars. Their projected separations from O-type stars on the sky is similar to (or even more isolated than) that of normal RSGs in the LMC with initial masses of only 10-15 M_{\odot} . This requires that the observed WN3/O3 stars have similar lifetimes and come from a similar initial mass range as typical RSGs. This new class is therefore distinct from the classical WR stars (WN and WC) that arise from higher initial mass (i.e. roughly $> 32 M_{\odot}$ for WN and $> 50 M_{\odot}$ for WO/WC Groh et al. 2013). In this lower mass range, radiation-driven stellar winds are too weak for the WN3/O3 stars to have shed their H envelopes via winds. Their relative isolation and longer lifetimes therefore suggest that they have been stripped of the H envelopes through binary evolution.

Considering a range of binary evolution models, we propose a plausible scenario for the evolutionary origin of WN3/O3 stars, where they are the stripped primary stars in binary systems with a low-mass secondary and relatively wide initial orbital separation. This leads to highly non-conservative mass transfer, so that after the mass transfer phase has ended, the secondary has accreted little mass and remains faint, whereas the more luminous primary has been

¹ Note that WN3/O3 stars do not yet have the dense CSM required to yield a SN Ibn if they were to explode in their current state. This material is ejected in precursor eruptions a few years before the SN. Our point here is only that SNe Ibn may have moderately massive (initially 10-20 M_{\odot}) and sometimes isolated stripped envelope progenitors, similar to WN3/O3 stars.

stripped of its H envelope and appears as a WN3/O3 star. The secondary contributes a small fraction of the total visible light, and radial velocity variations due to orbital motion are likely to be small in many cases, allowing them to easily have escaped detection so far. We suggest that monitoring of these systems with high spectral resolution may reveal the presence of faint companions, and can provide a direct test of our proposed origin for WN3/O3 stars.

Finally, we note that WN3/O3 stars are excellent candidates for SN Ib progenitors. Because of their low-mass and (presumed) faint secondary, they are more readily observable than stripped stars with a higher-mass companion that has gained mass. They therefore offer a way to constrain the physical properties of likely progenitors for Type Ib and possibly also Type Ibn explosions, both of which seem to favor more isolated environments than SNe Ic and SNe Ic-BL. It would be good to search for WN3/O3 stars in the Milky Way, or if they cannot be detected, to understand why they may not exist at the same luminosities at higher metallicity.

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